FINAL TECHNICAL REPORT

DEVELOPMENT OF AN OPERATIONAL MULTI-SENSOR AND MULTI-CHANNEL AEROSOL ASSIMILATION PACKAGE

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14. ABSTRACT

Aeeurate aerosol and visibility foreeasts are eritieal to both civilian and military applications. To improve the Navy's eleetro-optieal propagation foreeast eapability, the world's first operational aerosol assimilation model was developed for improving the short and long-term forecasts of NAAPS through the assimilation of the over-water MODIS aerosol produets. In this project, the eapability of over-land aerosol data assimilation was studied, a multi-sensor data assimilation technique was evaluated, and a prototype of a system that assimilates MODIS fine model aerosol optieal depth ratio was developed for improving model representation of aerosol speciation. Extending beyond the seope of this study, a 3-D aerosol assimilation package was eonstrueted, which is designed to improve the aeeuraey of NAAPS aerosol vertieal profiles by assimilating data from CALIPSO. With knowledge gained from the multi-sensor analysis, the long-term aerosol trend was also studied for elimate related applieations. This researeh projeet yielded a total of ten authored or eoauthored peer-reviewed journal papers and more than twenty conferenee presentations.

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ABSCTRACT

Accurate aerosol and visibility forecasts are critical to both civilian and military applications. To improve the Navy's electro-optical propagation forecast capability, the world's first operational aerosol assimilation model (NAVDAS-AOD) was developed for improving the short and long-term forecasts of the Navy Aerosol Analysis and Prediction System (NAAPS) through the assimilation of the over-water Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol products. In this project, the capability of over-land aerosol data assimilation was studied, a multi-sensor data assimilation technique was evaluated, and a prototype of a system that assimilates MODIS fine model aerosol optical depth ratio was developed for improving model representation of aerosol speciation. Extending beyond the scope of this study, a 3-D aerosol assimilation package was constructed, which is designed to improve the accuracy of NAAPS aerosol vertical profiles by assimilating data from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO). With knowledge gained from the multi-sensor analysis, the long-term aerosol trend was also studied for climate related applications. This research project yielded a total of ten authored or coauthored peer-reviewed journal papers and more than twenty conference presentations.

LONG-TERM GOALS

Accurate visibility forecasts are necessary for military operations and for field applications of optically-sensitive equipment. For this reason, the US Navy developed the world's first operational global aerosol model. However, model forecast skill is limited by a lack of observations over oceans and in data-denied areas. The long-term goal of this study is to improve the Navy's electro-optical propagation forecast capability through the use of multi-channel and multi-sensor aerosol data assimilation.

OBJECTIVES (from the original abstract)

Due to the significance of aerosol particles in visibility forecasting, air pollution, and global climate change studies, the modeling and successful prediction of aerosol events is of great interest to both military and civilian users. Recognizing this interest, the Naval Research Laboratory Marine Meteorology Division developed the Navy Aerosol Analysis and Prediction System (NAAPS), the world's only truly operational aerosol prediction model. NAAPS provides both aerosol and visibility forecasts for fleet operations. A recent study showed that by ingesting over-ocean satellite observations into NAAPS through data assimilation, NAAPS forecasting capability could be improved by 20-40%. This research study, however, also found that there are fundamental issues (e.g., issues that are identified as objectives of this study) remaining that must be addressed before a global aerosol data assimilation technique can realistically be ported to operational use.

The major goal of this proposal is to develop a near–real-time multi-sensor and multi-channel aerosol data assimilation analysis for NAAPS. We plan to use the NRL Atmospheric Variational Data Assimilation System (NAVDAS) coupled with NAAPS and remotely sensed aerosol optical properties (e.g., aerosol optical depth) to produce an operational aerosol assimilation package for a global aerosol optical depth and mass concentration analysis. The specific objectives are as follows:

(1) Develop an over-land (with bright surface areas) aerosol data assimilation capability;
(2) Improve observational data coverage through a multi-sensor data fusion/data assimilation technique;
(3) Utilize multi-channel information to improve the accuracy of NAAPS aerosol vertical profiles and speciation; and
(4) Develop a better parameterization for characterizing model forecasting errors.

WORK COMPLETED

The over-ocean and over-land data-assimilation capability has been developed with the use of the data-assimilation quality aerosol products from the Moderate Resolution Imaging Spectroradiometer (MODIS) in collaboration with Dr. Hyer and Dr. Reid from NRL (*Shi et al., 2011, Hyer et al., 2011*). The over-ocean assimilation package is currently running operationally at FNMOC, and the over-land assimilation section is being operated in a research mode at NRL.

A multi-sensor data assimilation method has been developed and evaluated using MODIS, Multi-angle Imaging SpectroRadiometer (MISR), MODIS DeepBlue, and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) aerosol products (*Zhang et al., BACIMO, 2010; Zhang et al., Aerosol Observability Workshop, 2010*). A prototype of an aerosol assimilation scheme that aims to improve aerosol speciation by utilizing the MODIS fine mode optical depth ratio was also developed. A sensitivity study of the parameterization for characterizing model forecasting errors has also been conducted with a 2D/3D Var coupled assimilation method (*Zhang et al., 2011; Campbell et al., 2010*).

In addition to the original research objectives of this study, research was also conducted based on new needs that were discovered during the study. An example of such research is the development of a 3-D CALIPSO assimilation scheme, where the original proposal includes only the development of a vertical CALIPSO climatology (*Zhang et al., 2011; Campbell et al., 2010*). As the backup sensor for the post-MODIS and MISR era, the AVHRR aerosol product has also been evaluated for its applicability for data assimilation even though the AVHRR data is considered to be low in scientific quality due to coarse spatial and spectral resolution. Finally, as an extension of a previous study, clear sky and other cloud-related contextual biases existing in satellite aerosol products were studied (*Zhang and Reid, 2009*), and long-term aerosol optical depth variations over global oceans were examined (*Zhang and Reid, 2010*). A detailed list of the work completed is:

Research conducted within the scope of the proposed study: Four sections of research efforts related to multi-sensor assimilation were conducted (collaborating with NRL scientists Dr. Jeff Reid, Dr. Edward Hyer, and Dr. James Campbell):

(1) Developed data assimilation quality MODIS aerosol products for future implementation in data assimilation. A new version of the MODIS aerosol product, collection 5, has been released by the MODIS aerosol team. Using a total of ten years of Terra MODIS (2000-2009) and eight years of Aqua MODIS (2002-2009), we developed quality assurance and empirical correction procedures for generating data-assimilation-friendly over-water MODIS aerosol products. This study has been published (Shi et al., 2011). We also participated in research led by Dr. Hyer and Dr. Reid from NRL on the development of a data-assimilation-friendly over-land MODIS aerosol product. This study has also been published for an AMT publication (Hyer et al., 2011).

(2) Developed multi-sensor data assimilation over land and ocean using data-assimilation-quality over-land and -ocean MODIS and MISR aerosol products (Zhang et al., BACIMO, 2010; Zhang et al., Aerosol Observability Workshop, 2010).

(3) Evaluated the MODIS fine mode to total aerosol optical depth (η) product for multi-channel assimilation capability. A prototype package for improving aerosol speciation by assimilating MODIS fine mode aerosol optical depth ratio was built with the joint support from the project N00014-10-0816. Further testing and evaluation will be conducted with the support of the project N00014-10-0816.

(4) Evaluated the MISR and MODIS DeepBlue aerosol products data assimilation. In this multi-year effort, ten years (2000-2009) of MODIS DeepBlue and MISR aerosol products were evaluated for the development of noise-reduced and bias-corrected MISR and

MODIS Deep Blue aerosol products. Currently, the development of data-assimilation quality MODIS DeepBlue and MISR data is in the final stage of construction, which is jointly supported by the project N00014-10-0816.

Research conducted beyond the scope of the proposed study: The PI and collaborators (collaborating with NRL scientists Dr. Jeff Reid, Dr. Edward Hyer, and Dr. James Campbell) explored new research directions that will benefit the long-term goal of the proposed study. These accomplishments include:

(1) Development of a 3-D aerosol assimilation scheme using the CALIPSO data. In realizing the need for improving the vertical representation of aerosols in the model, an aerosol assimilation package that couples 2-D aerosol assimilation (using MODIS and MISR products) with 3-D aerosol assimilation (using CALIPSO data) was constructed (Zhang et al., 2011). This research work is jointly supported by the project N00014-10-0816.

(2) Evaluation of decadal regional and global aerosol trends using data-assimilation-quality MODIS, operational MODIS, and operational MISR over-ocean products (Zhang and Reid, 2010).

(3) Analysis of clear sky and other cloud-related contextual biases existing in satellite aerosol products. This work is built upon the extension of project N00014-08-1-0264 (Zhang and Reid, 2009).

(4) Finally, evaluation of the AVHRR aerosol product for its potential use for data assimilation. The scientific quality of the AVHRR aerosol product is considered to be low due to a limited number of spectral channels and relatively coarse spatial resolution. However, AVHRR has a long and inherited history, and most importantly we expect AVHRR sensors to remain functioning even in the post-MODIS and MISR era. In collaboration with Dr. Hyer and Dr. Reid from NRL, we evaluated the NOAA Advanced Clear-Sky Processor for Ocean (ACSPO) product and studied the inclusion of the AVHRR aerosol product as a backup for the Navy's operational aerosol forecasts.

RESULTS

An analysis of the collection 5 MODIS over-ocean aerosol optical depth product for its implication in aerosol assimilation (abstract from the ACPD paper, Shi et al., 2011)

As an update to our previous use of the Collection 4 MODIS over-water AOD data, we examined ten years of Terra and eight years of Aqua Collection 5 data for their potential use in aerosol data assimilation. Uncertainties in the over-water MODIS AOD were studied as functions of observing conditions, such as surface characteristics, aerosol optical properties, and cloud artifacts. Empirical corrections and quality assurance procedures were developed and compared to collection 4 data. After applying quality assurance and empirical correction procedures, the Root-Mean-Square-Error (RMSE) in the MODIS Terra and Aqua AOD are reduced by 30% and 10–20%, respectively. Ten years of Terra and eight years of Aqua quality-assured level 3 MODIS over-water aerosol products were produced. The newly developed MODIS over-water aerosol products will be used in operational aerosol data assimilation and

aerosol climatology studies, and the products will also be useful to other researchers who are using MODIS satellite products in their projects.

Multi-sensor data assimilation using the data-assimilation grade over-land and -ocean MODIS and MISR aerosol products (Zhang et al., BACIMO, 2010; Zhang et al., Aerosol Observability Workshop, 2010)

Multi-sensor data assimilation and its impacts on both over-ocean and over-land aerosol forecasting capabilities were evaluated using the data assimilation quality MODIS over-ocean, the data assimilation quality MODIS over-land (collaborating with Dr. Hyer and Dr. Reid from NRL), and Version 1 of the quality-assured MISR aerosol products (a new version is under development). For one year of evaluation (2007) against AERONET ground-based data, our study suggested that NAVDAS-AOD could improve the accuracy of the analysis field over both land, with a 24% reduction in absolute error, and ocean, with a 40% reduction in absolute error. Our study also suggested that over-ocean aerosol analyses benefited from the MODIS aerosol product, but adding more sensors only resulted in small improvements. However, multi-sensor assimilation is critical to the over-land aerosol assimilation method as improvements were observable with each new sensor added.

Analysis of the MODIS over-ocean fine mode to total aerosol optical depth ratio (η) for multi-channel aerosol assimilation

We studied MODIS-derived over-ocean fine mode to total aerosol optical depth (η) values for multi-channel aerosol assimilation. η is often used as a surrogate for aerosol type as large η values are generally related to fine mode aerosols, such as sulfate and smoke aerosols, and small η values typically indicate sea salt and dust aerosols. A data-assimilation-quality η product was developed by applying bias corrections and noise removal procedures to data from the seven MODIS channels that report aerosol property values along with a spectral convolution method from O'Neil et al. (2003) that is used to estimate modified/corrected η values. Finally, a prototype of an assimilation package that assimilates MODIS η was developed. Preliminary results from the MODIS over-water fine mode aerosol optical depth fraction (η) assimilation show that a low bias in fine mode aerosol optical depth from NAAPS has been reduced with the use of η assimilation. Further evaluation of the η assimilation will be conducted with the support of the project N00014-10-0816.

Further development of the data-assimilation-quality MODIS Deep Blue and MISR aerosol products (Shi et al., 2010, AGU; Zhang et al., 2010, AGU)

Nine years of MISR aerosol products (2000-2008) over both land and ocean were evaluated against ground-based AERONET observations. Our study suggested that the over-ocean MISR aerosol product meets the reported accuracy. Additionally, the over-land MISR aerosol product proved to be more robust than that of MODIS and can be used for future inter-comparisons with MODIS aerosol products over land. However, our study also suggested that cloud contamination, especially cirrus cloud contamination, is still a problem for the MISR aerosol product. Therefore, quality assurance and quality check procedures are necessary before implementing MISR into data assimilation cycles and/or before using it for cross-sensor inter-

comparisons. Similarly, uncertainties in the MODIS DeepBlue aerosol products were studied as functions of surface characteristics, observational conditions, and aerosol microphysics properties, specifically over North Africa. We found that DeepBlue AOD values (with QA flags equal to "very good") are in good agreement with the AERONET data, especially in North African regions. However, uncertainties are found to be associated with aerosol microphysics (aerosol type or aerosol size), surface albedo, and scattering angle. With joint support from project N00014-10-0816, the final steps of developing data-assimilation-quality products from the MISR and MODIS DeepBlue products are in progress.

Three dimensional aerosol assimilation using CALIPSO (Zhang et al., 2011):

Using NAVDAS-3D, a prototype for the CALIPSO aerosol data assimilation scheme has been developed through the collaborative efforts from Dr. Reid (NRL) and Dr. Campbell (UCAR/NRL). As a first step, a data-assimilation-friendly CALIPSO aerosol product was created. Then, a 3-D CALIPSO data assimilation scheme was further developed to incorporate the 3-D CALIPSO data into the aerosol prediction and forecasting cycles. We improved the representation of the observational and background error statistics of the 3-D version of NAVDAS-AOD, and extensive sensitivity studies were conducted for evaluating the performance of the system. Lastly, we examined the possibility of assimilating both 2-D satellite aerosol data (MODIS, MISR) and 3-D aerosol data (CALIPSO) using a coupled 2D/3D Var aerosol assimilation package. Surprisingly, contrary to the common belief of the community, we found that including CALIPSO data reduced the absolute error by more than 10% for the 48-h over land aerosol optical depth prediction. This exercise proves that CALIPSO data, although sparse in coverage, could still be used for improving aerosol and visibility forecasts. This encouraging result suggests that near real time 3-D space-borne lidar products from future sensors may become important data sources for the Navy.

A decadal regional and global trend analysis of aerosol optical depth using data-assimilation grade over-water MODIS and Level 2 MISR aerosol products (abstract from the ACPD paper, Zhang and Reid, 2010)

Using ten years (2000-2009) of data-assimilation quality Terra MODIS and MISR aerosol products, as well as 7 years of Aqua MODIS data, we studied both regional and global aerosol trends over oceans. This included both natural and data-assimilation-grade versions of the products. Contrary to some previous studies that showed a decreasing trend in aerosol optical depth (AOD) over global oceans, we found a statistically negligible trend. After correcting for what appears to be aerosol signal drift from the radiometric calibration of both MODIS instruments, we found MODIS and MISR agreed on a statistically negligible global trend in AOD of 0.0003 per year. Our study also suggests that AODs over the Indian Bay of Bengal, the east coast of Asia, and the Arabian Sea show statistically significant increasing trends of 0.07, 0.06, and 0.06 per ten years for MODIS, respectively. Similar increasing trends were found with MISR data, but with less relative magnitude. These trends reflect respective increases in the optical intensity of aerosol events in each region: anthropogenic aerosols over the east coast of China and the Indian Bay of Bengal and a stronger influence from dust events over the Arabian Sea. Negative AOD trends are found off the coasts of Central America, the east coast of North America, and the west coast of Africa. However, confidence levels are low in these regions, which indicate that longer periods of observation are necessary to be conclusive.

An analysis of clear sky and contextual biases (abstract from the paper Zhang and Reid, 2009):

Clear sky and other cloud-related contextual biases are critical, yet unsolved mysteries for aerosol related climatological studies using satellite observations. For the first time, we simulated contextual biases over ocean using 2-years of NAAPS products that include MODIS AOD assimilation. We compared model-derived AOD in regions with and without observations, and we found that sampling yields a negligible seasonal, globally-averaged AOD bias (< 5%). Biases are more pronounced in regions with frequent overcast skies and high aerosol loadings, such as Southeast Asia and mid-latitude South America. This suggests that contextual biases may develop from transport covariance and other observing biases. Lastly, we found that, over remote regions of the ocean under cloud decks, a slight increase in aerosol optical depth values could exist compared with cloud free regions. However, this increase is still small relative to cloud artifacts in the retrieval.

Evaluation of the potential use of the AVHRR ACSPO product as a backup satellite product

AVHRR sensors have been providing continuous observations of the Earth and atmospheric system for decades, and these sensors will continue providing weather and environmental monitoring for the foreseeable future. In collaboration with Dr. Hyer and Dr. Reid from NRL, we evaluated aerosol retrievals from the NOAA Advanced Clear-Sky Processor for Ocean (ACSPO) products, including their potential use as a backup for the NRL aerosol forecasting and assimilation system. Our results show that with the use of noise-reduced and bias-removed AVHRR aerosol retrievals, the accuracy of the NAAPS AOD analysis field indeed improved. This result supports the possible future implementation of AVHRR products into Navy visibility forecasts.

IMPACT/APPLICATIONS

Current validation efforts suggest that multi-sensor assimilation is critical to over-land aerosol assimilation. Improvements are observable with each new sensor added. Uncertainties in the NAAPS AOD analysis were reduced by 40% over ocean and 20-30% over land for multi-sensor assimilation (e.g. *Zhang et al., BACIMO, 2010*). The use of the CALIPSO data improves the vertical representation of the NAAPS aerosol field. Also, although sparse in coverage, the improvements from the CALIPSO assimilation are observed up to the 48 hour forecast.

TRANSITIONS

Codes for constructing a data-assimilation-quality MODIS collection 5 over water product have been delivered to NRL Monterey and are currently running operationally at FNMOC.

RELATED PROJECTS

This project is tightly coupled to a number of ONR 322 programs at the Marine Meteorology Division Aerosol and Radiation Section working on the further development of the Navy's aerosol forecasting capabilities. These projects include an integrated effort with the Earth Sciences Applications project of Dr. J. S. Reid on the development of NAVDAS-AOD, the model integration with the Large Scale Aerosol Modeling Development project of Dr. D. L. Westphal, the NASA ESSF project of Yingxi Shi, and the PECASE program of Dr. Jianglong Zhang.

PUBLICATIONS

Zhang, J., J. R. Campbell, J. S. Reid, D. L. Westphal, N. L. Baker, W. F. Campbell, and E. J. Hyer, Evaluating the Impact of Assimilating CALIOP-derived Aerosol Extinction Profiles on a Global Mass Transport Model, Geophysical Research Letters, In Press, 2011 [published, refereed].

Zhang, J. and Reid, J. S.: A decadal regional and global trend analysis of the aerosol optical depth using a data-assimilation grade over-water MODIS and Level 2 MISR aerosol products, Atmos. Chem. Phys. Discuss., 10, 18879-18917, doi:10.5194/acpd-10-18879-2010, 2010 [published, refereed].

Zhang, J. and J. S. Reid, An analysis of clear sky and contextual biases using an operational over ocean MODIS aerosol product, Geophysical Research Letters, 36, L15824, doi:10.1029/2009GL038723, 2009 [published, refereed]..

Shi, Y., J. Zhang, J. S. Reid, B. Holben, E. J. Hyer, and C. Curtis: An analysis of the collection 5 MODIS over-ocean aerosol optical depth product for its implication in aerosol assimilation, Atmos. Chem. Phys., 11, 557-565, doi:10.5194/acp-11-557-2011, 2011 [published, refereed].

Hyer, E. J., J. S. Reid, J. S., and J. Zhang, An over-land aerosol optical depth data set for data assimilation by filtering, correction, and aggregation of MODIS Collection 5 optical depth retrievals, Atmos. Meas. Tech., 4, 379-408, doi:10.5194/amt-4-379-2011, 2011 [published, refereed].

Patadia F., S. A Christopher, J. Zhang, Development of Empirical Angular Distribution Models for Smoke Aerosols - Part 1. Methods, J. Geophys. Res., D14203, doi:10.1029/2010JD015033, 2011 [published, refereed].

Smirnov, A., B. N. Holben, D. M. Giles, I. Slutsker, N. T. O'Neill, T. F. Eck, A. Macke, P. Croot, Y. Courcoux, S. M. Sakerin, T. J. Smyth, T. Zielinski, G. Zibordi, J. I. Goes, M. J. Harvey, P. K. Quinn, N. B. Nelson, V. F. Radionov, C. M. Duarte, R. Losno, J. Sciare, K. J. Voss, S. Kinne, N. R. Nalli, E. Joseph, K. Krishna Moorthy, D. S. Covert, S. K. Gulev, G. Milinevsky, P. Larouche, S. Belanger, E. Horne, M. Chin, L. A. Remer, R. A. Kahn, J. S. Reid, M. Schulz, C. L. Heald, J. Zhang, K. Lapina, R. G. Kleidman, J. Griesfeller, B. J. Gaitley, Q. Tan, and T. L. Diehl: Maritime Aerosol Network as a component of AERONET – first results and comparison with global aerosol models and satellite retrievals, Atmos. Meas. Tech., 4, 583-597, doi:10.5194/amt-4-583-2011, 2011 [published, refereed].

Sayer, M. A., N. C. Hsu, C. Bettenhausen, J. Zhang and coauthors, SeaWiFS Ocean Aerosol Retrieval (SOAR): algorithm, validation, and comparison with other datasets, submitted to JGR, 2011 [Submitted, refereed].

Campbell, J. R., J. S. Reid, D. L. Westphal, J. Zhang, E. J. Hyer and E. J. Welton, CALIOP aerosol subset processing for global aerosol transport model data assimilation, IEEE Journal

of Selected Topics in Applied Earth Observations and Remote Sensing, Volume: 3, Issue: 2, 10.1109/JSTARS.2010.2044868, 2010 [published, refereed].

Reid, J.S., E. J. Hyer, E. M. Prins, D. L. Westphal, J. Zhang, J. Wang, S. A. Christopher, C. A. Curtis, C. C. Schmidt, D. P. Eleuterio, K. A. Richardson, and J. P. Hoffman, Global Monitoring and Forecasting of Biomass-Burning Smoke: Description of and Lessons from the Fire Locating and Modeling of Burning Emissions (FLAMBE) Program, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, JSTARS-2009-00034, 2009 [Published, refereed].

Zhang J., J. Reid, D. Westphal, J. Campbell, E. Hyer, and N. Baker, Multi-sensor Data Assimilation Using MODIS MISR and CALIPSO Aerosol Products, the 9th Joint Center for Satellite Data Assimilation Science Workshop, Greenbelt, MD, May 24-25 11, 2011.

Johnson, R. S., J. Zhang, Reid, J. Campbell, E. Hyer, D. Westphal, N. Baker, P. Xian, Methods of NAAPS Evaluation, International Cooperative for Aerosol Prediction, Ensemble Forecasts and Data Assimilation, Boulder, CO, May 11-13, 2011.

Reid, J. S., J. Zhang, B. Sampson, J. Hansen, and W. Sessions, Climatological-Persistence Models (CLIPERs), International Cooperative for Aerosol Prediction, Ensemble Forecasts and Data Assimilation, Boulder, CO, May 11-13, 2011.

Zhang J., J. Reid, E. Hyer, J. Campbell, and D. Westphal, Critical analysis of ten years of AOD trends over global oceans from MODIS, MISR, and NAAPS (Invited), Abstract A14C-08 presented at 2010 Fall Meeting, AGU, San Francisco, Calif., 13-17 Dec, 2010.

Westphal, D., J. Campbell, J. Reid, E. Hyer, J. Zhang, D. M. Winker, Fulfilling Operational Requirements for Operational Aerosol Data Assimilation (Invited), Abstract A33G-02 presented at 2010 Fall Meeting, AGU, San Francisco, Calif., 13-17 Dec, 2010.

Zhang J., E. Hyer, J. Campbell, Y. Shi, J. Reid, D. Westphal, Overview of the data assimilation quality satellite aerosol products, Abstract A31A-0024 presented at 2010 Fall Meeting, AGU, San Francisco, Calif., 13-17 Dec, 2010.

Campbell J., J. S. Reid, J. L. Tackett, D. Westphal, D. M. Winker, J. Zhang, Satellite Lidar Data Assimilation For Improved Global Aerosol Forecasting: Lessons Learned From CALIOP, With an Eye Toward EarthCARE, Abstract A31A-0021 presented at 2010 Fall Meeting, AGU, San Francisco, Calif., 13-17 Dec, 2010.

Shi, Y, Zhang, J, J. Reid, and C. Hsu, Evaluation of the MODIS Deep Blue aerosol product over the North Africa Regions for aerosol forecasts related applications, Abstract A31A-0025 presented at 2010 Fall Meeting, AGU, San Francisco, Calif., 13-17 Dec, 2010.

Zhang J., J. Reid, D. Westphal, E. Hyer, C. Curtis, N. Baker, J. Campbell, and P. Xian, The Operational Aerosol Data Assimilation System for US Navy Aerosol and Visibility Forecasts, BACIMO conference, Omaha, NE, April, 2010

Zhang J., J. Reid, D. Westphal, E. Hyer, N. Baker, J. Campbell, multi-sensor aerosol data assimilation, Aerosol Observability Workship, Monterey, CA, April, 2010.

Smirnov A., B. N. Holben, M. Chin, R. A. Kahn, L. A. Remer, M. Schulz, J. S. Reid, C. L. Heald, S. Kinne, T. L. Diehl, B. J. Gaitley, R. G. Kleidman, J. Griesfeller, J. Zhang, Q. Tan, K. Lapina, P. Kishcha, Maritime Aerosol Network as a component of AERONET – current status and comparison with satellite retrievals and global aerosol transport models, AeroCom Workshop, Oriel College, University of Oxford, 2010.

Campbell J., E. Hyer, J. Zhang, J. Reid, D. Westphal, P. Xian, and M. Vaughan, Advances In Global Aerosol Modeling Applications Through Assimilation of Satellite-Based Lidar

Measurements, Geophysical Research Abstracts, Vol. 12, EGU2010-5593-1, 2010, EGU General Assembly 2010.

Shi, Y., J. Zhang, J. S. Reid, E. Hyer, Evaluation of MISR Aerosol Optical Depth Product for Aerosol Data Assimilation and Multi-Sensor Data Fusion, *AGU Fall Annual Meeting, 2009.*

Campbell, R. J., J. Zhang, J. S. Reid, D. L. Westphal, Assimilating CALIPSO Aerosol Profiles for Global Transport Modeling, *AGU Fall Annual Meeting, 2009.*

Reid, S. J., J. Zhang, E. Hyer, J. R. Campbell, S. A. Christopher, R. A. Ferrare, G. G. Leptoukh, P. W. Stackhouse, Observability considerations for multi-sensor and product fusion: Bias, information content, and validation, *AGU Fall Annual Meeting, 2009.*

Shi, Y., J. Zhang, J. S. Reid, Near 10 Years Analysis of Aerosol Optical Depth Over Oceans from AQUA and TERRA MODIS, *AAAR 28th Annual Conference*, 2009.

Hyer, J. E, J. S. Reid, J. Campbell, P. Xian, J. Zhang, C. Curtis, D. Westphal, Evaluating a global biomass burning source term using a global aerosol model, *AAAR 28th Annual Conference*, 2009.

Campbell, J. R., J. Zhang, J. S. Reid, D. L. Westphal, V. Khade and J. Hansen, Assimilating CALIPSO Aerosol Profiles to Investigate Saharan Dust Storm Phenomenology, *CloudSat/CALIPSO Science Workshop*, Monona Terrace, Madison, 28-31 July 2009.

Zhang J., J. S. Reid, N. Baker, D. L. Westphal and E. J. Hyer, An Operational Aerosol Data Assimilation System (NAVDAS-AOD), the 6th Joint Center for Satellite Data Assimilation Science Workshop, Greenbelt, MD, June 10-June 11, 2008.

Shi, Y., J. Zhang, and J. S. Reid, development of the data assimilation quality MODIS and MISR aerosol products for data integration and assimilation, *Eos Trans. AGU, 89*(53), Fall Meet. Suppl., Abstract A21G-04, 2008.

Kalashnikova O. V., R. A. Kahn, M. Chin, J. Zhang, and G. Leptoukh, Mineral dust characterization over the North Atlantic/ Saharan desert regions from combined satellite aerosol retrievals and AERONET observations for transport model applications, *Eos Trans. AGU, 89*(53), Fall Meet. Suppl., Abstract A21G-08, 2008.